Big-bang nucleosynthesis with a long-lived CHAMP including helium-4 spallation process

Masato Yamanaka (KEK)

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collaborators
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Introduction

Long-lived charged massive particle (CHAMP)

- Predicted in many models of beyond SM
- Various hunting
(collider experiments, neutrino telescope, etc.)
- Cosmological constraints on its property
(Big-Bang Nucleosynthesis(BBN), large scale structure, etc.)

One of the interesting objects for particle physics, astrophysics, and nuclear physics

Introduction

Candidate of long-lived CHAMP: NLSP stau in SUSY models

NLSP: Next Lightest SUSY particle

Scenarios predicting long-lived stau

- neutralino LSP scenario (phase space suppression)

  [S. Profumo, K. Sigurdson, P. Ullio and M. Kamionkowski, PRD71]

  [T. Jittoh, J. Sato, T. Shimomura and MY, PRD73]

- gravitino LSP scenario (Planck suppressed coupling)

  [W. Buchmuller, K. Hamaguchi, M. Ratz and T. Yanagida, PLB588]

  [J. L. Feng, S. Su and F. Takayama, PRD70]

- etc.

LSP: Lightest SUSY particle

Introduction

Modifications to light elements abundances in the BBN

- Destruction of nuclei by its decay products
- Catalyzed fusion by forming bound state with nuclei
- etc.

Important for comprehension of stau property and each scenario

(1) To identify what exotic reactions are induced by
each type of long-lived stau

(2) To understand what light elements are over-produced
or over-destructed by each type of reactions

Introduction

Topics in this talk

- Proposing a new process (^{4}He spallation process)
- Search for cosmologically favored parameter space in the MSSM including the new process

Important for comprehension of stau property and each scenario

(1) To identify what exotic reactions are induced by each type of long-lived stau

(2) To understand what light elements are over-produced or over-destructed by each type of reactions

1. Introduction

2. Exotic nuclear reactions with long-lived stau

2.1 Catalyzed fusion

2.2 ^{4}He spallation process

3. Cosmologically favored parameter space in MSSM

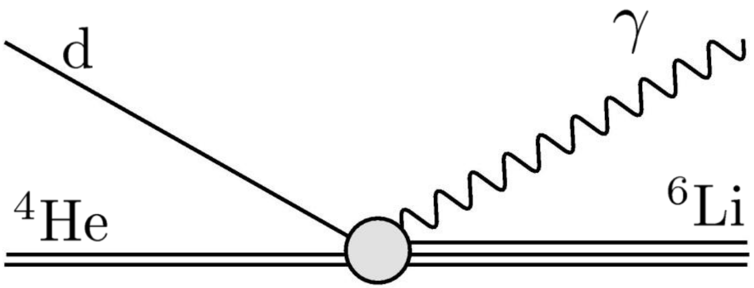
4. Summary

Exotic nuclear reactions with long-lived stau

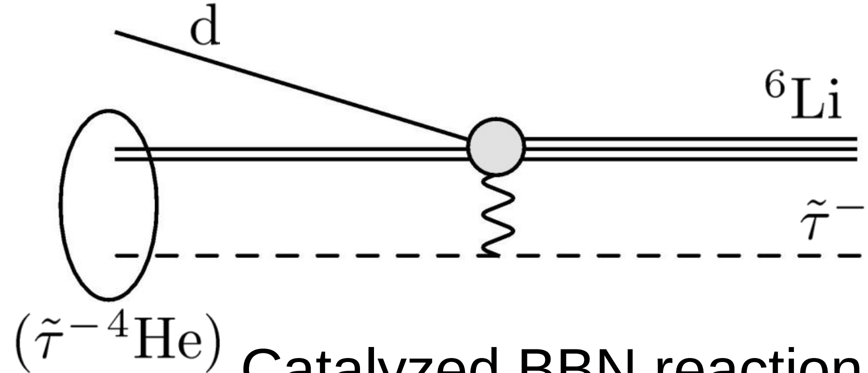
(1) Catalyzed fusion [M. Pospelov, PRL98]

Bound state formation via EM int. $\tilde{\tau} + {}^{4}\mathrm{He} \to (\tilde{\tau}^{-}\,{}^{4}\mathrm{He})$

⇒ Catalyzed fusion $(\tilde{\tau}^{-}\,{}^{4}\mathrm{He}) + \mathrm{d} \to {}^{6}\mathrm{Li} + \tilde{\tau}^{-}$



Standard BBN reaction

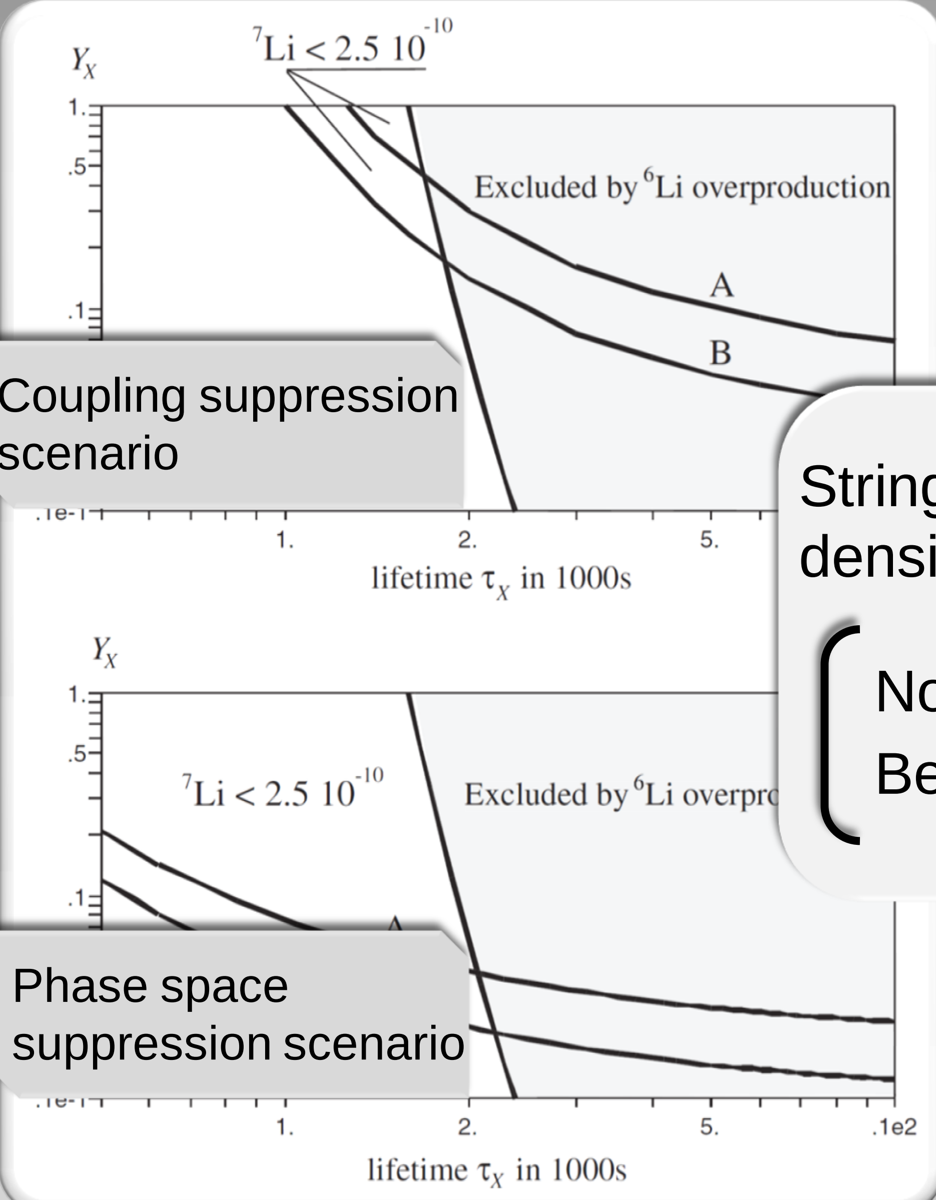


Catalyzed BBN reaction

$$\frac{\langle \sigma v \rangle_{\mathrm{catalyzed}}}{\langle \sigma v \rangle_{\mathrm{standard}}} \simeq 10^{7}$$

(∵ Standard: forbidden E1 transition
Catalyzed: α transfer reaction)

(1) Catalyzed fusion



Coupling suppression scenario

Phase space suppression scenario

Catalyzed fusion

$$(\tilde{\tau}^{-}\,{}^4\mathrm{He}) + \mathrm{d} \to {}^6\mathrm{Li} + \tilde{\tau}^{-}$$

Stringent constraint on stau lifetime and density to evade ^{6}Li overproduction

(Note!!
Before including spallation process)

[C. Bird, K. Koopmans and M. Pospelov, PRD78]

(2) ^{4}He spallation process

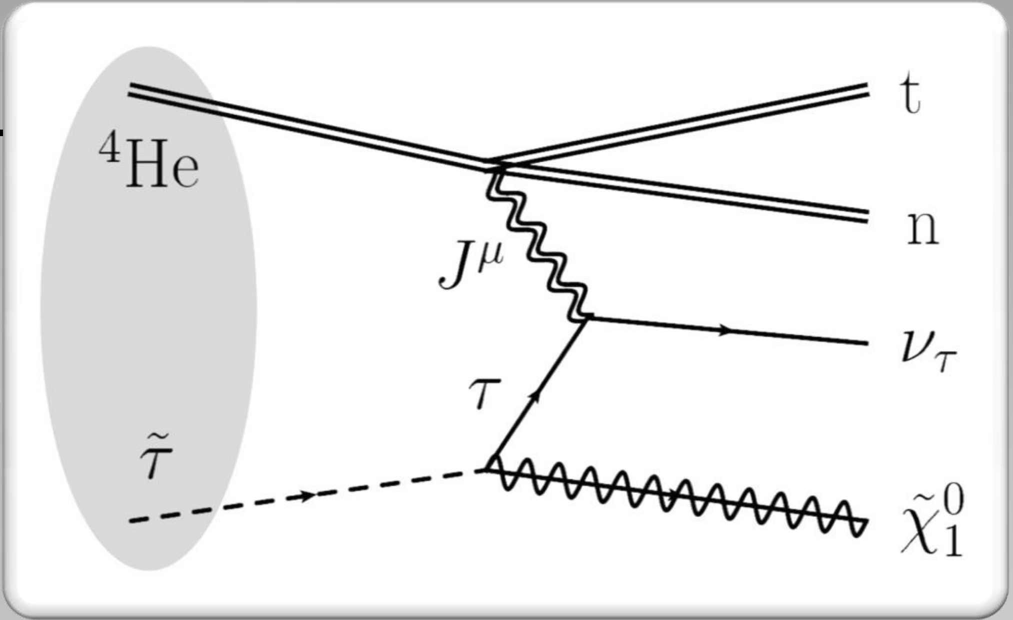
[T. Jittoh, K. Kohri, M. Koike, J. Sato, K. Sugai, K. Yazaki, and MY, PRD84]

Bound state formation via EM int.

$$\tilde{\tau} + {}^4\mathrm{He} \to (\tilde{\tau}\,{}^4\mathrm{He})$$

Spallation process

$$(\tilde{\tau}\,{}^4\mathrm{He}) \to \tilde{\chi}_1^0 + \nu_\tau + \mathrm{t} + \mathrm{n}$$

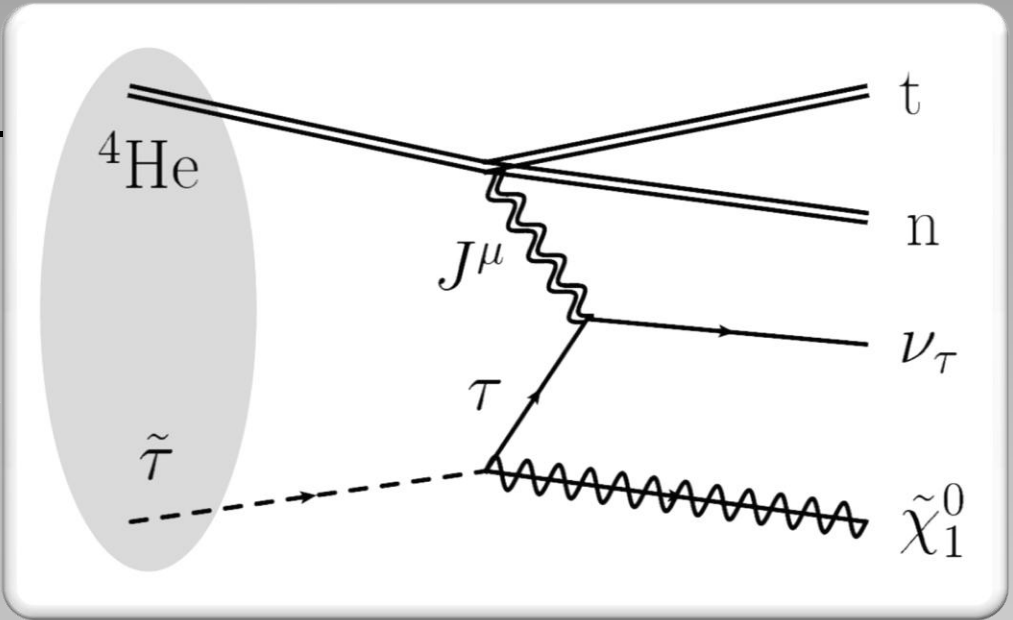


Reaction rate $\Gamma\big((\tilde{\tau}\,{}^4\mathrm{He}) \to \tilde{\chi}_1^0 \nu_\tau \mathrm{tn}\big) = |\psi|^2 \cdot \sigma \mathrm{v_{tn}}$

(2) ^{4}He spallation process

Bound state formation via EM int.

$$\tilde{\tau} + {}^4\mathrm{He} \rightarrow (\tilde{\tau}\,{}^4\mathrm{He})$$



Spallation process

$$(\tilde{\tau}\,{}^4\mathrm{He}) \rightarrow \tilde{\chi}_1^0 + \nu_\tau + \mathrm{t} + \mathrm{n}$$

Reaction rate $\Gamma\left((\tilde{\tau}\,{}^4\mathrm{He}) \rightarrow \tilde{\chi}_1^0 \nu_\tau \mathrm{tn}\right) = |\psi|^2 \cdot \sigma \mathrm{v}_{\mathrm{tn}}$

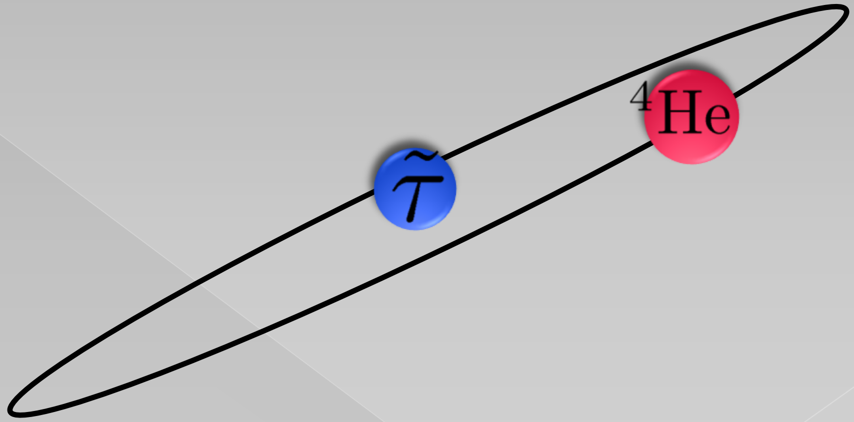
Overlap of initial state wave functions

(2) ^{4}He spallation process

Approximation

Localization of $\tilde{\tau}$ at center position in $(\tilde{\tau}\,{}^4\mathrm{He})$ $\left[\because\ m_{\mathrm{He}} \ll m_{\tilde{\tau}}\right]$

⇒ Overlap = ^{4}He wave function at the center position

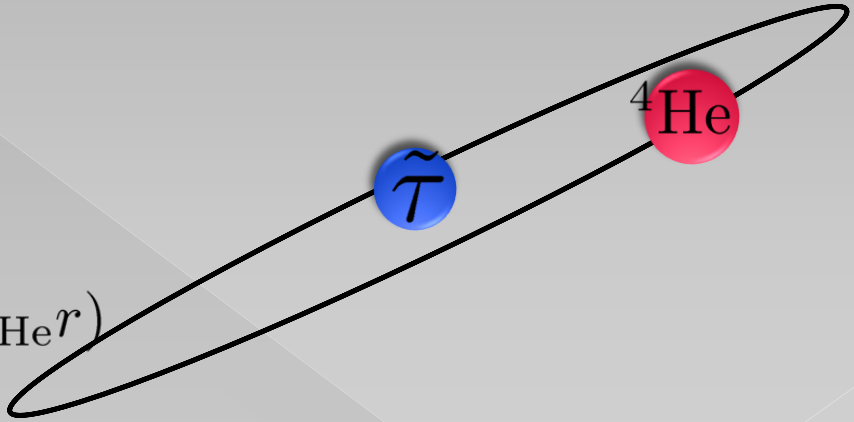


(2) ^{4}He spallation process

Approximation

Localization of $\tilde{\tau}$ at center position in $(\tilde{\tau}\,{}^4\mathrm{He})$ $\left[\because\ m_{\mathrm{He}} \ll m_{\tilde{\tau}}\right]$

⇨ Overlap = ^{4}He wave function at the center position



Wave function of ^{4}He

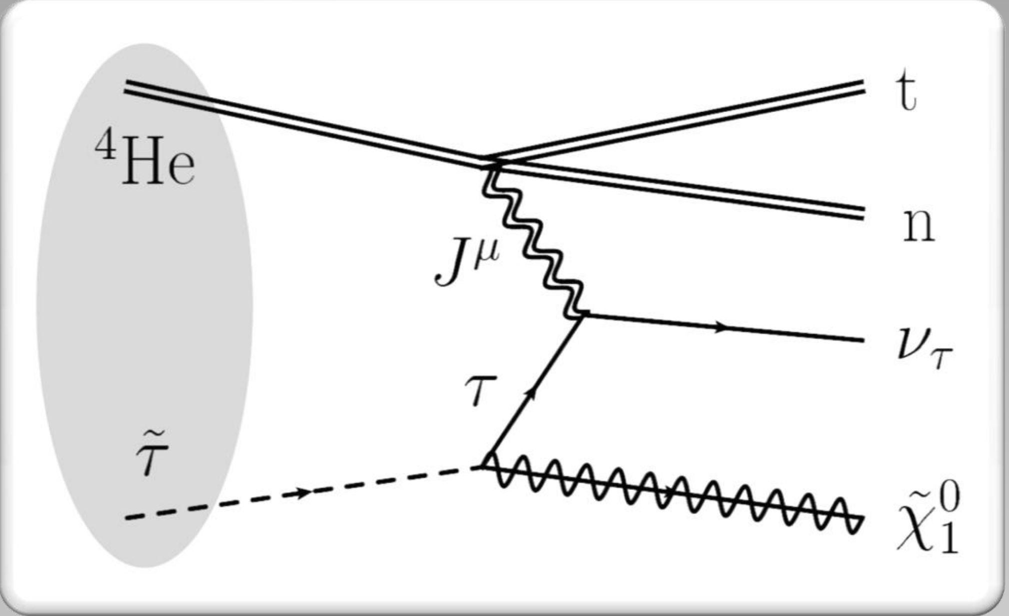
$$\psi_{1\mathrm{S}}^{(\mathrm{He})}(r;Z) = \frac{(Z\alpha m_{\mathrm{He}})^{3/2}}{\sqrt{\pi}} \exp(-Z\alpha m_{\mathrm{He}} r)$$

Overlap of wave functions $|\psi|^2 = |\psi_{1\mathrm{S}}^{(\mathrm{He})}(0;2)|^2 = \dfrac{(2\alpha m_{\mathrm{He}})^3}{\pi}$

(2) ^{4}He spallation process

Bound state formation via EM int.

$$\tilde{\tau} + {}^4\mathrm{He} \rightarrow (\tilde{\tau}\,{}^4\mathrm{He})$$



Spallation process

$$(\tilde{\tau}\,{}^4\mathrm{He}) \rightarrow \tilde{\chi}_1^0 + \nu_\tau + \mathrm{t} + \mathrm{n}$$

Reaction rate $\Gamma\big((\tilde{\tau}\,{}^4\mathrm{He}) \rightarrow \tilde{\chi}_1^0 \nu_\tau \mathrm{tn}\big) = |\psi|^2 \cdot \sigma \mathrm{v}_{\mathrm{tn}}$

Cross section of elemental reaction

(2) ^{4}He spallation process

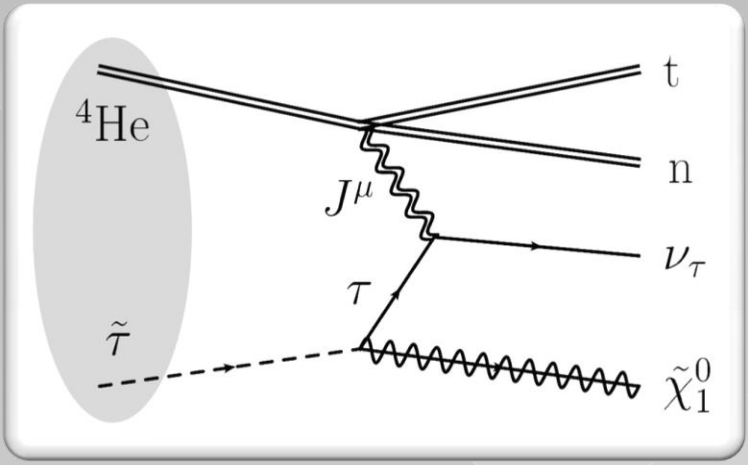
Cross section of elemental reaction

$$\sigma v_{\rm tn} = \frac{1}{2E_{\tilde{\tau}}} \int \frac{d^3\boldsymbol{p}_\nu}{(2\pi)^3 2E_\nu} \frac{d^3\boldsymbol{p}_{\tilde{\chi}}}{(2\pi)^3 2E_{\tilde{\chi}}} \frac{d^3\boldsymbol{q}_{\rm n}}{(2\pi)^3} \frac{d^3\boldsymbol{q}_{\rm t}}{(2\pi)^3}$$

$$\times \left| \mathcal{M}\big((\tilde{\tau}^4{\rm He}) \to \tilde{\chi}_1^0 \nu_\tau {\rm tn}\big) \right|^2 (2\pi)^4 \delta^{(4)}(p_{\tilde{\tau}} + p_{\rm He} - p_\nu - q_{\rm t} - q_{\rm n})$$

Amplitude

$$\mathcal{M}\big((\tilde{\tau}^4{\rm He}) \to \tilde{\chi}_1^0 \nu_\tau {\rm tn}\big)$$
$$= \langle {\rm t\, n}\, \tilde{\chi}_1^0\, \nu_\tau | \mathcal{L}_{\rm int} | ^4{\rm He}\, \tilde{\tau} \rangle$$
$$= \langle {\rm t\, n} | J^\mu | ^4{\rm He} \rangle \; \langle \tilde{\chi}_1^0\, \nu_\tau | j_\mu | \tilde{\tau} \rangle$$



Leptonic part; calculated straightforwardly

Calculation of hadronic matrix element $\langle \mathrm{t\,n}|J^\mu|{}^4\mathrm{He}\rangle$

- Building up wave functions of ^{4}He, t, d, and n

Requirement: anti-symmetric under the exchange of two nucleons

spin, isospin part (anti-symmetric)

$$|{}^4\mathrm{He}\rangle = \frac{1}{2\sqrt{6}}\big[|\mathrm{pnpn}\rangle\big(|\uparrow\uparrow\downarrow\downarrow\rangle + |\downarrow\downarrow\uparrow\uparrow\rangle - |\uparrow\downarrow\downarrow\uparrow\rangle - |\downarrow\uparrow\uparrow\downarrow\rangle\big)$$
$$+ \,\ldots\ldots + |\mathrm{nnpp}\rangle\big(-|\uparrow\downarrow\uparrow\downarrow\rangle + |\uparrow\downarrow\downarrow\uparrow\rangle + |\downarrow\uparrow\uparrow\downarrow\rangle - |\downarrow\uparrow\downarrow\uparrow\rangle\big)\big]$$

spatial part (symmetric)

$$\psi_{\mathrm{He}}(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{r}_3, \boldsymbol{r}_4) = \left(2\frac{a_{\mathrm{He}}^3}{\pi^3}\right)^{3/4}$$
$$\times \exp\left\{-a_{\mathrm{He}}\left[\boldsymbol{r}_1^2 + \boldsymbol{r}_2^2 + \boldsymbol{r}_3^2 + \boldsymbol{r}_4^2 - \frac{1}{4}(\boldsymbol{r}_1 + \boldsymbol{r}_2 + \boldsymbol{r}_3 + \boldsymbol{r}_4)^2\right]\right\}$$

$$a_{\mathrm{He}} = \frac{9}{16}\frac{1}{(R_{\mathrm{m}})^2_{\mathrm{He}}}, \quad a_{\mathrm{t}} = \frac{1}{2}\frac{1}{(R_{\mathrm{m}})^2_{\mathrm{t}}} \qquad (R_{\mathrm{m}} : \text{matter radius})$$

Calculation of hadronic matrix element $\langle \mathrm{t\,n} | J^{\mu} | {}^4\mathrm{He} \rangle$

- Explicit form of the hadronic current

In non-relativistic limit $$J_{\mu} = V_{\mu} + g_A A_{\mu} \to (V_0,\ g_A A_i)$$

V^0 : Time component in vector current

A^i : Spatial components in axial vector current

g_A : axial vector coupling

Taking operators as a sum of a single-nucleon operators $$V^0 = \sum_{a=1}^{4} \tau_a^- \mathrm{e}^{\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}_a}, \quad A^i = \sum_{a=1}^{4} \tau_a^- \sigma_a^i \mathrm{e}^{\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}_a}$$

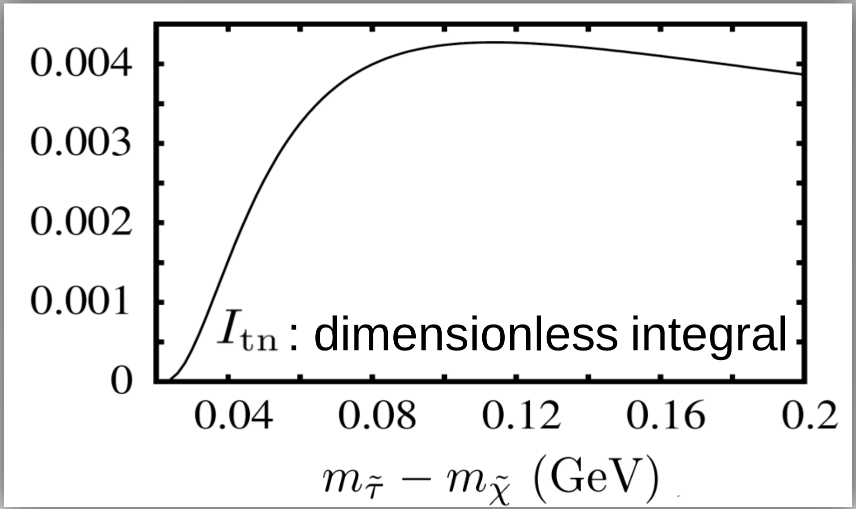
τ_a^-: isospin ladder operator of a-th nucleon

σ_a^i: spin operator of a-th nucleon

Calculation result of cross section

Cross section of elemental reaction

$$\sigma v_{\mathrm{tn}} = \frac{8}{\pi^2}\left(\frac{32}{3\pi}\right)^{3/2} g^2 \tan^2\theta_W \sin^2\theta_\tau (1+3g_A^2) G_F^2 \times \Delta_{\mathrm{tn}}^4 \frac{m_{\mathrm{t}} m_{\mathrm{n}}}{m_{\tilde{\tau}} m_{\tilde{\tau}}^2} \frac{a_{\mathrm{He}}^{3/2} a_{\mathrm{t}}^3}{(a_{\mathrm{He}}+a_{\mathrm{t}})^5} I_{\mathrm{tn}}$$



$$\Delta_{\mathrm{tn}} \equiv m_{\tilde{\tau}} - m_{\tilde{\chi}} + \Delta_{\mathrm{He}} - \Delta_{\mathrm{t}} - \Delta_{\mathrm{n}} - E_{\mathrm{b}}$$

$$\Delta_{\mathrm{He}} = m_{\mathrm{He}} - 4A,$$
$$\Delta_{\mathrm{t}} = m_{\mathrm{t}} - 3A,$$
$$\Delta_{\mathrm{n}} = m_{\mathrm{n}} - A$$

A : Unified atomic mass unit

Evolution of stau-^{4}He bound state

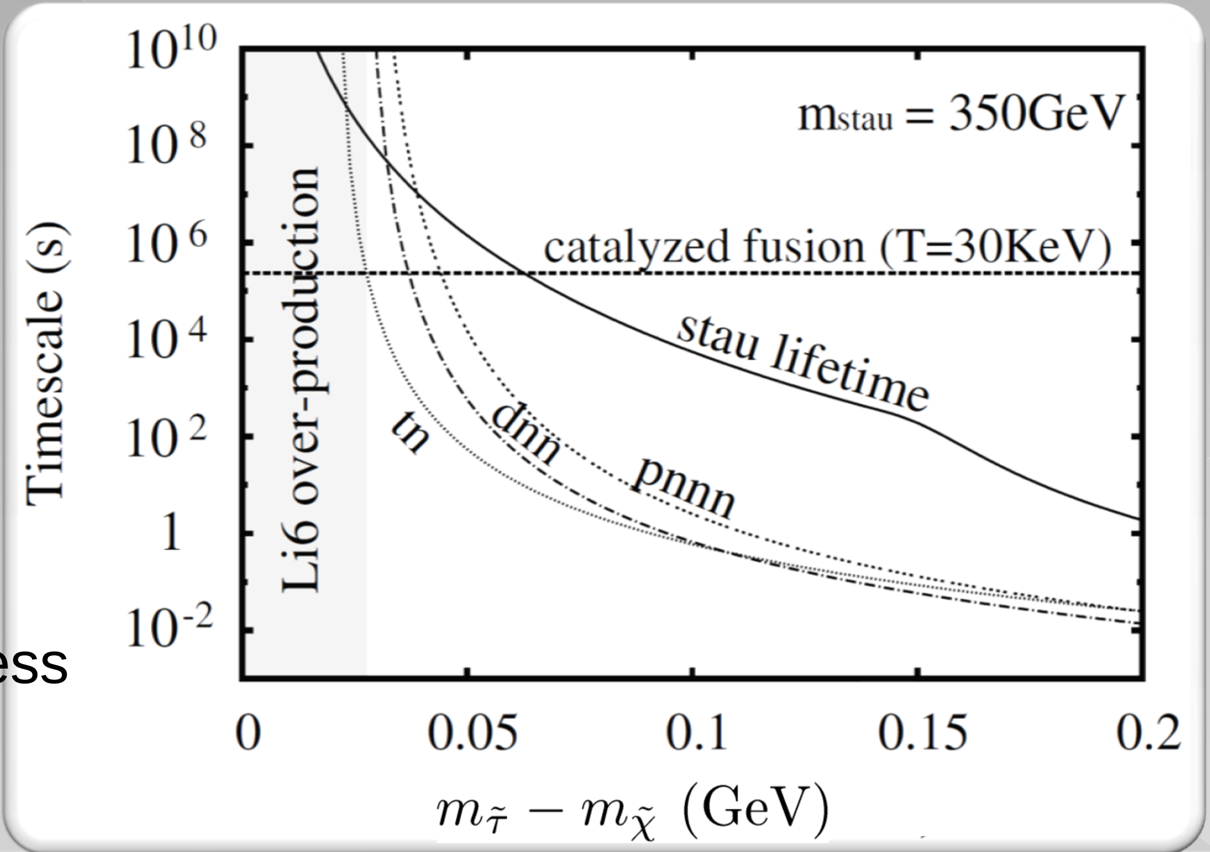
- Catalyzed fusion ⟹ ^{6}Li over-production
- Spallation process ⟹ d and t over-production
- Standard particle decay ⟹ Free from BBN constraint

Important

Which is dominant process?

Evolution of stau-^{4}He bound state

- Catalyzed fusion ⇨ ^{6}Li over-production
- Spallation process ⇨ d and t over-production
- Standard particle decay ⇨ Free from BBN constraint



Time scale of each process

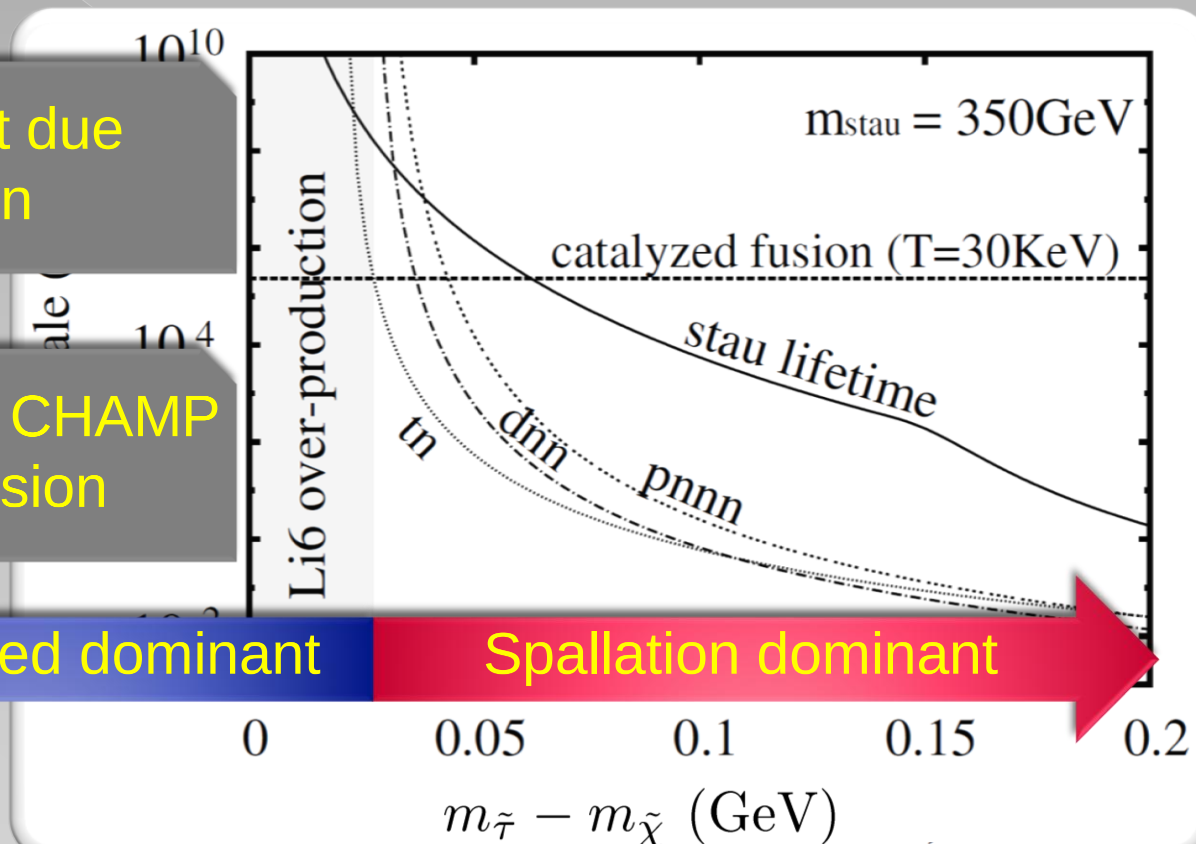
Evolution of stau-^{4}He bound state

Compared with catalyzed fusion

∵
- Large overlap of initial state wave functions
- Without external deuteron

More stringent constraint due to d and t over-production

For also other long-lived CHAMP by phase space suppression



Catalyzed dominant

Spallation dominant

Cosmologically Favored parameter space in MSSM

How to constrain the property of long-lived stau

Requirement in light of BBN

- Evading overproduction of d and t (^{4}He spallation process)
- Evading overproduction of ^{6}Li (catalyzed fusion)
- Solving the ^{7}Li problem (internal conversion)

Theoretical prediction $(4.15^{+0.49}_{-0.45}) \times 10^{-10}$

Discrepancy between them

^{7}Li problem

Observation $(1.26^{+0.29}_{-0.24}) \times 10^{-10}$

How to constrain the property of long-lived stau

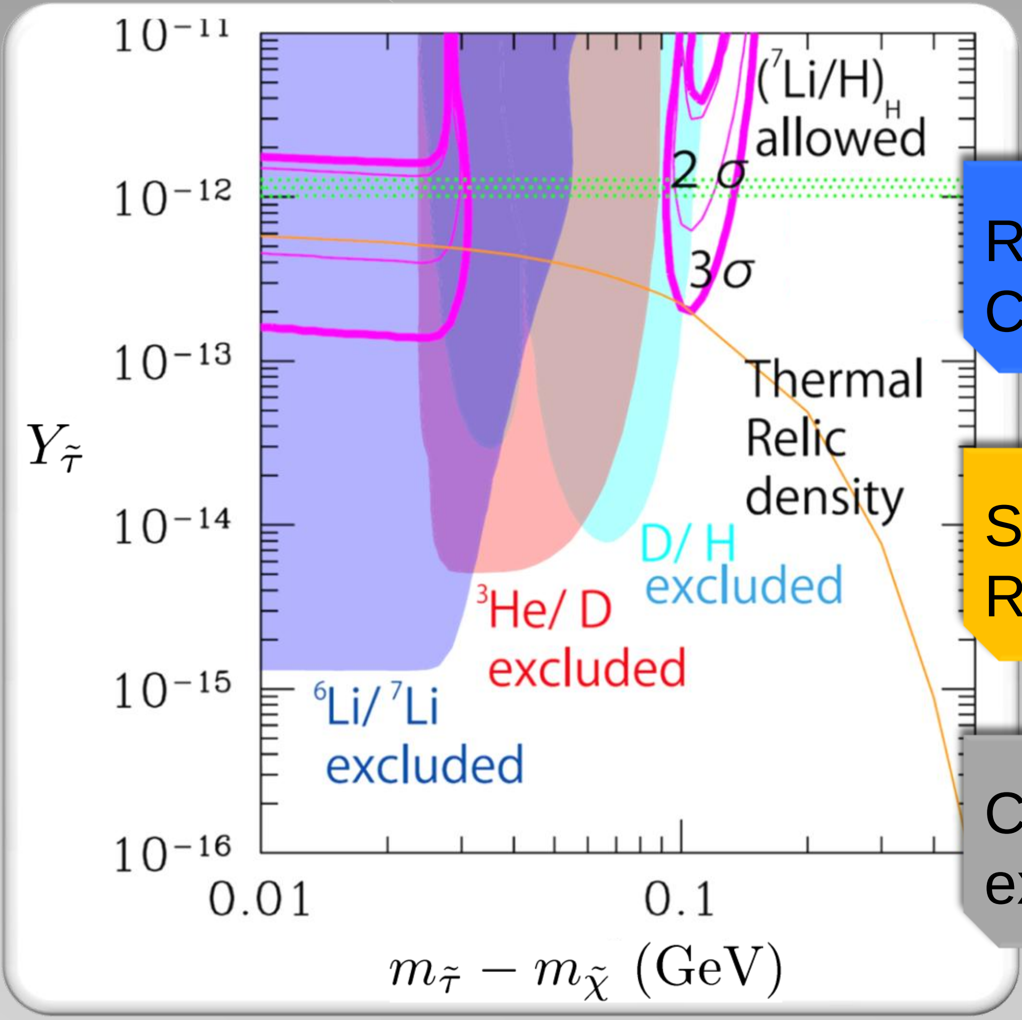
Requirement in light of BBN

- Evading overproduction of d and t (^{4}He spallation process)
- Evading overproduction of ^{6}Li (catalyzed fusion)
- Solving the ^{7}Li problem (internal conversion)

Requirement in light of dark matter

- Reproducing observed relic abundance of neutralino

Favored parameter space in MSSM

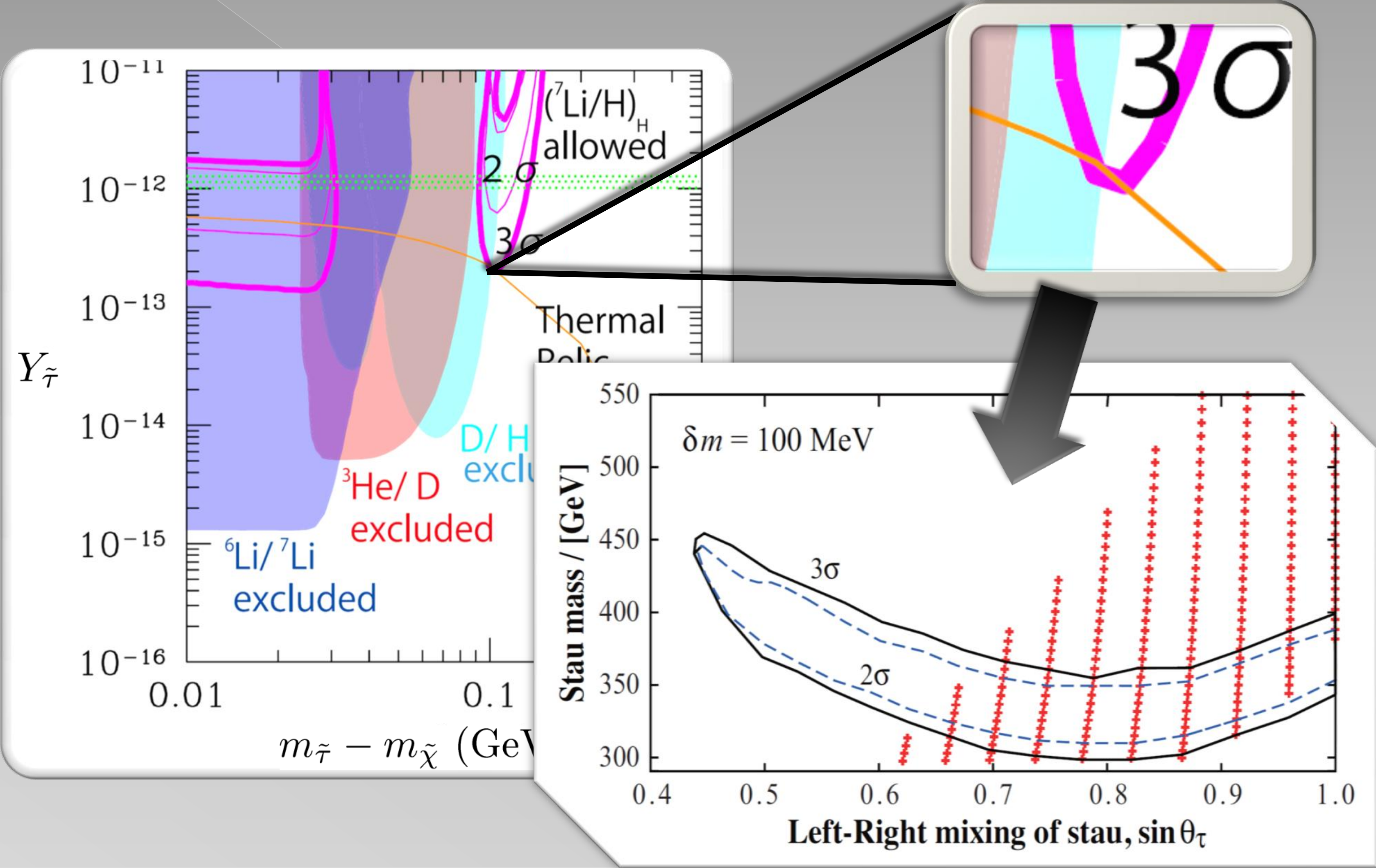


Region surrounded by purple line:
Consistent with observed ^{7}Li

Solid line (orange line):
Relic density of long-lived stau

Colored region:
excluded by over-production

Favored parameter space in MSSM



Prediction to observable from the physics of BBN and dark matter

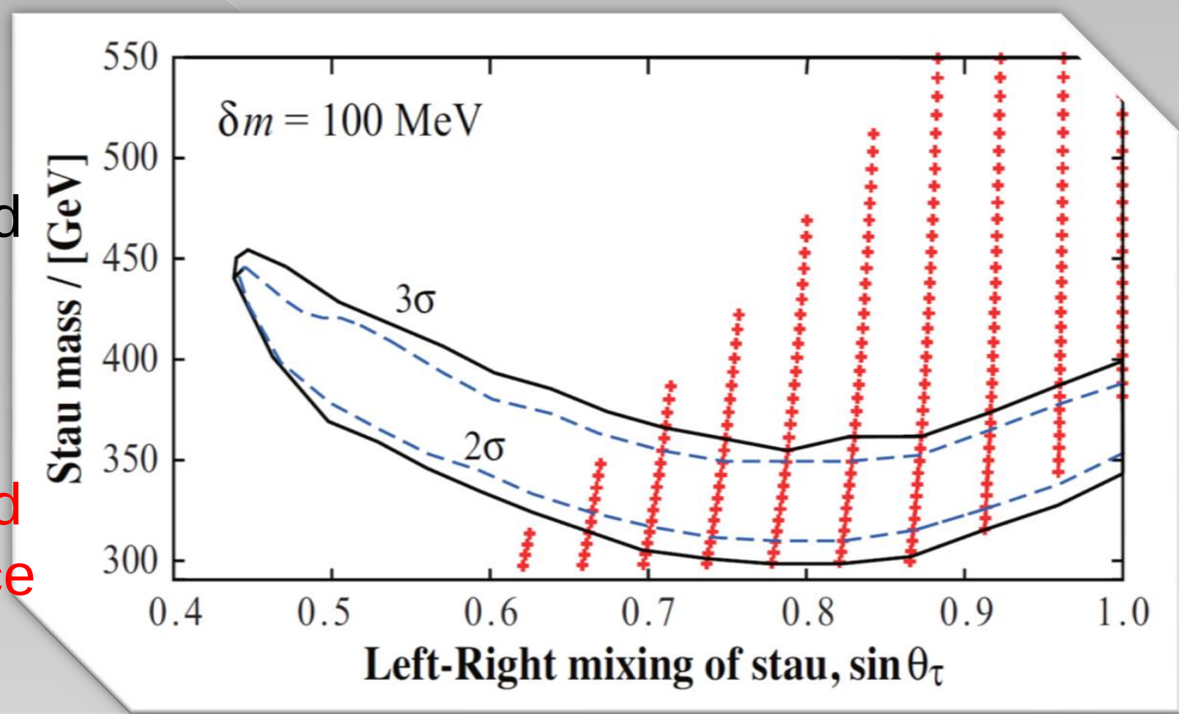
→ Complementary information for the test of MSSM in terrestrial experiments

Region in solid line:

Consistent with observed dark matter abundance

Red cross points:

Consistent with observed light elements abundance



Summary

Summary

- It is important for comprehension of the property of long-lived charged massive particle

  → To identify what exotic reactions are induced

  → To understand what nuclei are over-produced(-destructed)

- We investigated an impact of exotic reactions induced by long-lived stau, i.e.,

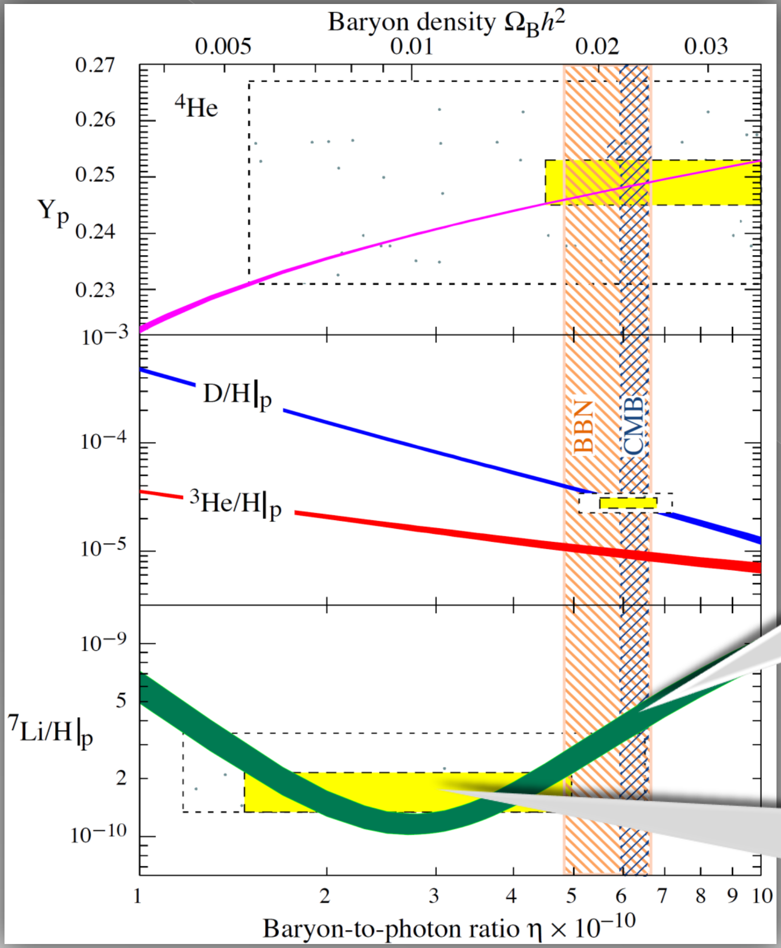
  - Catalyzed fusion process
  - Internal conversion process
  - ^{4}He spallation process (new proposal)

  on light elements abundances

- MSSM parameter is precisely predicted from the physics of BBN and dark matter, and it is useful information to test the model

Back-up slides

^{7}Li problem



Theoretical prediction $(4.15^{+0.49}_{-0.45}) \times 10^{-10}$

A. Coc, et al., astrophys. J. 600 (2004)

Discrepancy between them

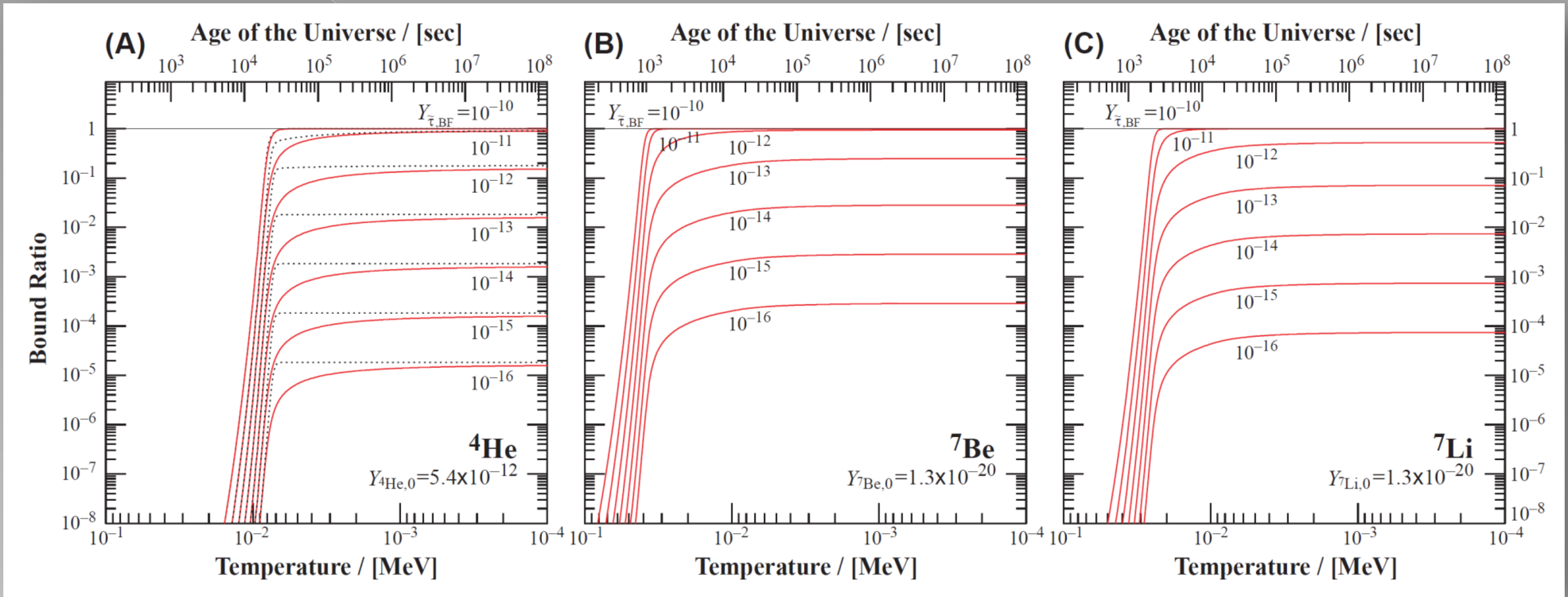
^{7}Li problem

Observation $(1.26^{+0.29}_{-0.24}) \times 10^{-10}$

P. Bonifacio, et al., Astronomy and Astrophysics, 462 (2007)

Solving the problem ⟺ Reducing ^{7}Li and ^{7}Be abundances

Formation rate of bound state



(2) Internal conversion

[T. Jittoh, K. Kohri, M. Koike, J. Sato, T. Shimomura and MY, PRD76 (2007)]

[C. Bird, K. Koopmans and M. Pospelov, PRD78 (2008)]

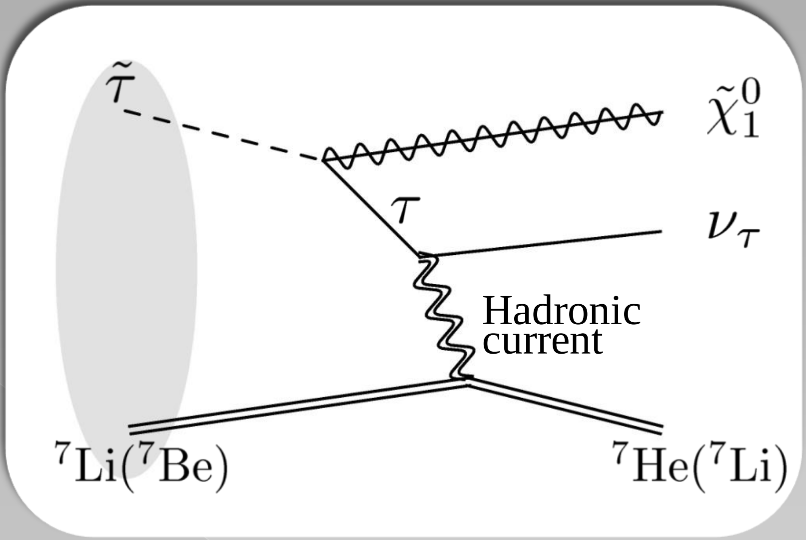
Bound state formation with ^{7}Li and/or ^{7}Be

$$\tilde{\tau}^- + {}^7\mathrm{Li}({}^7\mathrm{Be}) \to (\tilde{\tau}^- \, {}^7\mathrm{Li}({}^7\mathrm{Be}))$$

Internal conversion

$$(\tilde{\tau}^- \, {}^7\mathrm{Li}) \to \tilde{\chi}_1^0 + \nu_\tau + {}^7\mathrm{He}$$

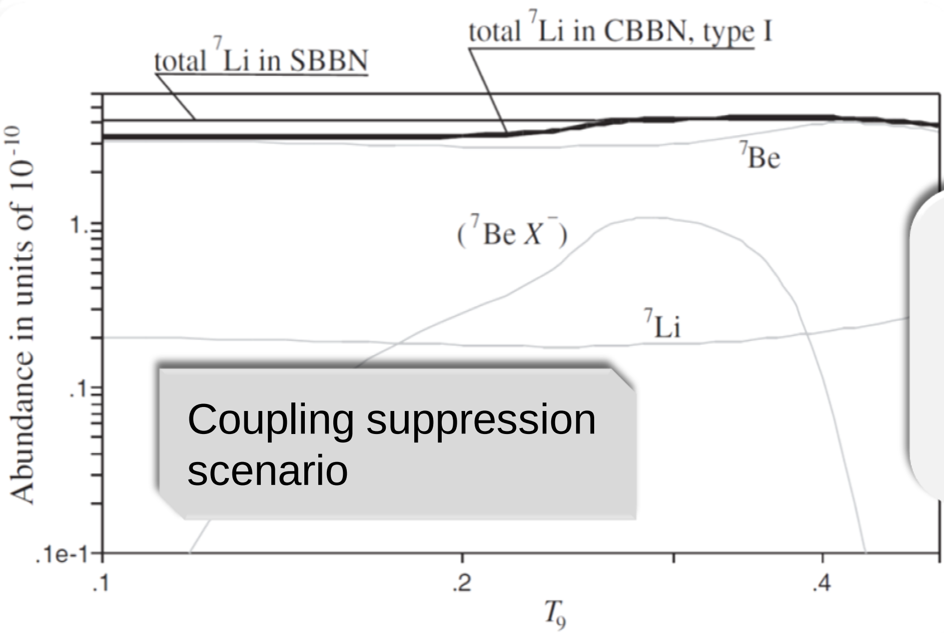
$$(\tilde{\tau}^- \, {}^7\mathrm{Be}) \to \tilde{\chi}_1^0 + \nu_\tau + {}^7\mathrm{Li}$$



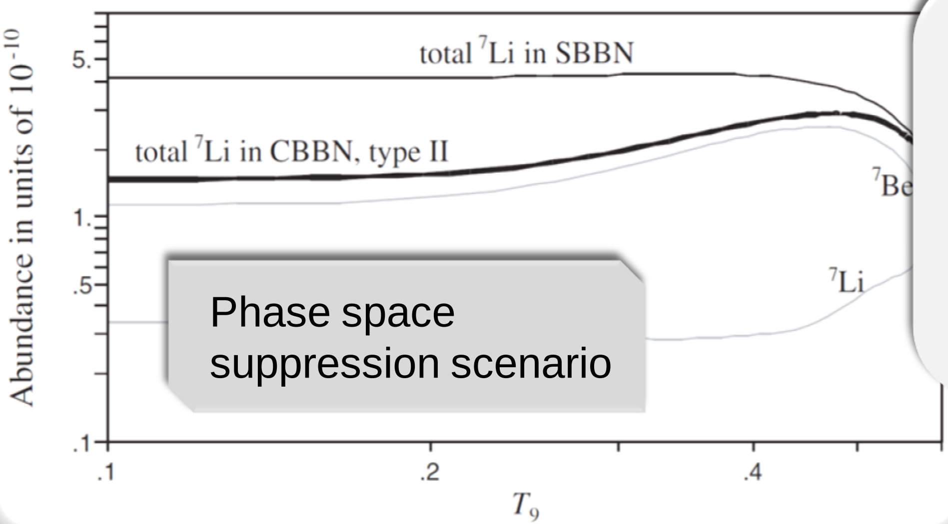
$$\frac{\text{Timescale of internal conversion}}{\text{Timescale of BBN era (}\sim\text{1sec)}} \ll 1$$

($\because$ Overlap of initial state wave functions (c.f. electron capture))

(2) Internal conversion



Coupling suppression scenario



Phase space suppression scenario

Constraint on the property of long-lived stau by evading over-destruction of ^{7}Li

Reducing ^{7}Li abundance compared with standard BBN

→ Solving the ^{7}Li problem

(In phase space suppression scenario)

[C. Bird, K. Koopmans and M. Pospelov, PRD78 (2008)]

(3) ^{4}He spallation process

Calculation result of $\langle \mathrm{t\,n}|J^\mu|{}^4\mathrm{He}\rangle$

$$\langle \mathrm{tn}|V^0|{}^4\mathrm{He}\rangle = \sqrt{2}\mathcal{M}_{\mathrm{tn}},$$

$$\langle \mathrm{tn}|g_A A^3|{}^4\mathrm{He}\rangle = -\sqrt{2}g_A\mathcal{M}_{\mathrm{tn}},$$

$$\langle \mathrm{tn}|g_A A^\pm|{}^4\mathrm{He}\rangle = \pm\sqrt{2}g_A\mathcal{M}_{\mathrm{tn}}$$

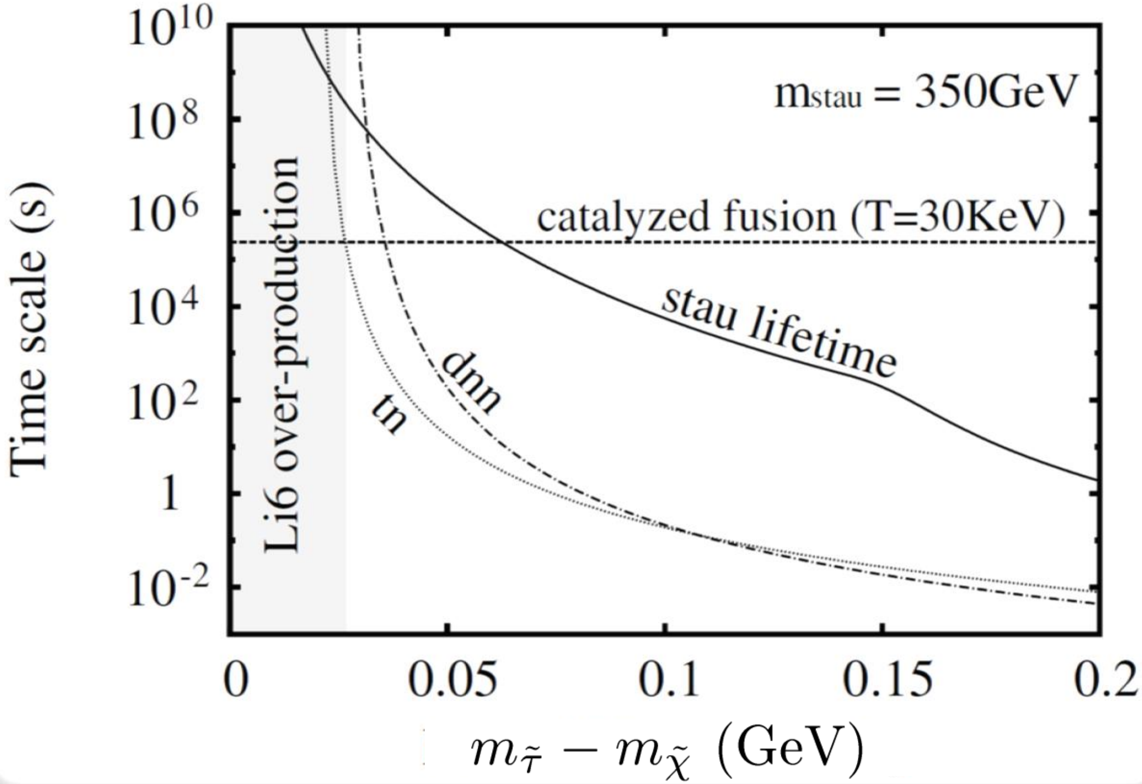
V^0 : Time component in vector current

A^i : Spatial components in axial vector current

g_A : axial vector coupling

$$\mathcal{M}_{\mathrm{tn}} = \left(\frac{128\pi}{3}\frac{a_{\mathrm{He}}a_{\mathrm{t}}^2}{(a_{\mathrm{He}}+a_{\mathrm{t}})^4}\right)^{3/4}\left\{\exp\left[-\frac{\boldsymbol{q}_{\mathrm{t}}^2}{3a_{\mathrm{He}}}\right] - \exp\left[-\frac{\boldsymbol{q}_{\mathrm{n}}^2}{3a_{\mathrm{He}}} - \frac{(\boldsymbol{q}_{\mathrm{t}}+\boldsymbol{q}_{\mathrm{n}})^2}{6(a_{\mathrm{He}}+a_{\mathrm{t}})}\right]\right\}$$

$$a_{\mathrm{He}} = \frac{9}{16}\frac{1}{(R_{\mathrm{m}})_{\mathrm{He}}^2},\ a_{\mathrm{t}} = \frac{1}{2}\frac{1}{(R_{\mathrm{m}})_{\mathrm{t}}^2} \quad (R_{\mathrm{m}} : \text{matter radius})$$

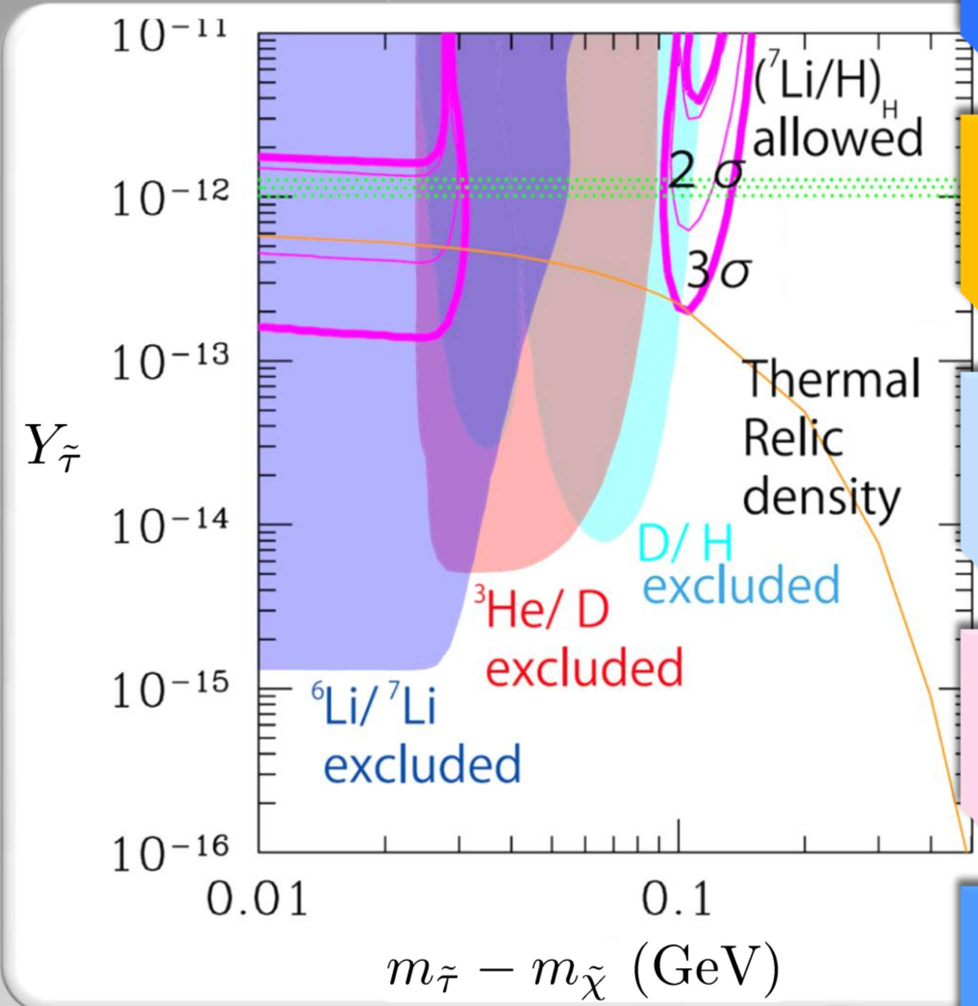


Time scale of each process

Input values

nucleus	$R_{\rm m}$ [fm]/[GeV^{-1}]	m_X [GeV]	Δ_X [GeV]
d	1.966 / 9.962	1.876	1.314×10^{-2}
t	1.928 / 9.770	2.809	1.495×10^{-2}
^{4}He	1.49 / 7.55	3.728	2.425×10^{-3}

Favored parameter space in MSSM



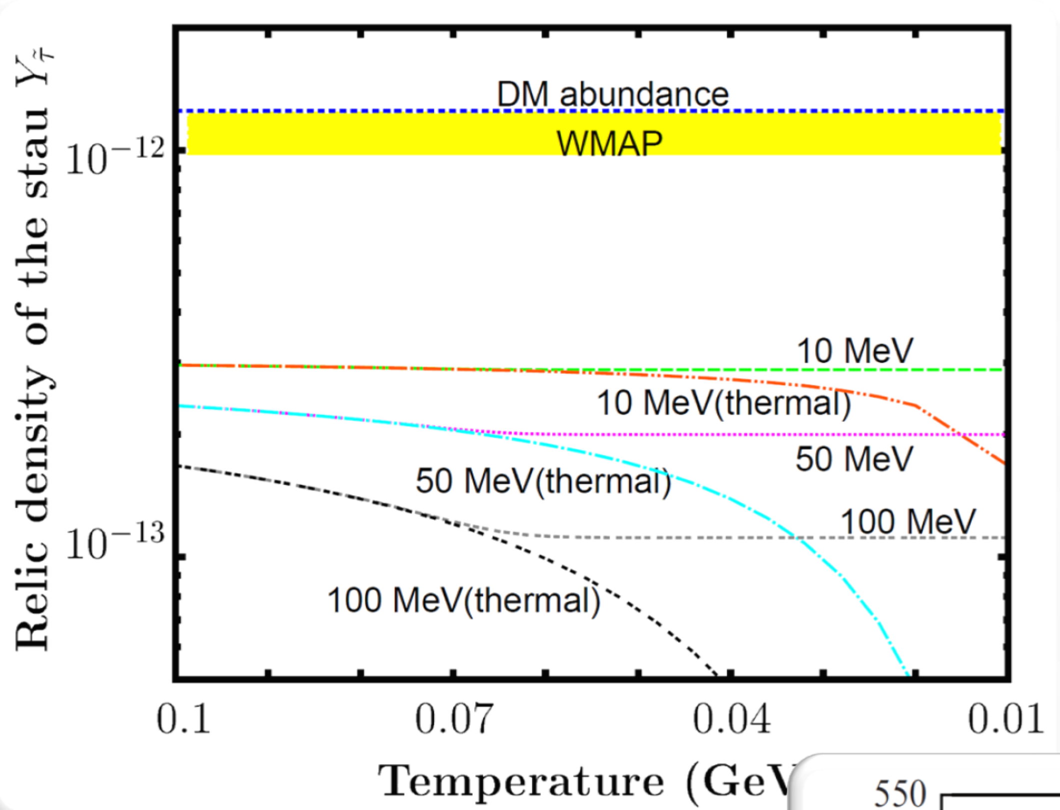
Region surrounded by purple line:
Consistent with observed ^{7}Li

Solid line (orange line):
Relic density of long-lived stau

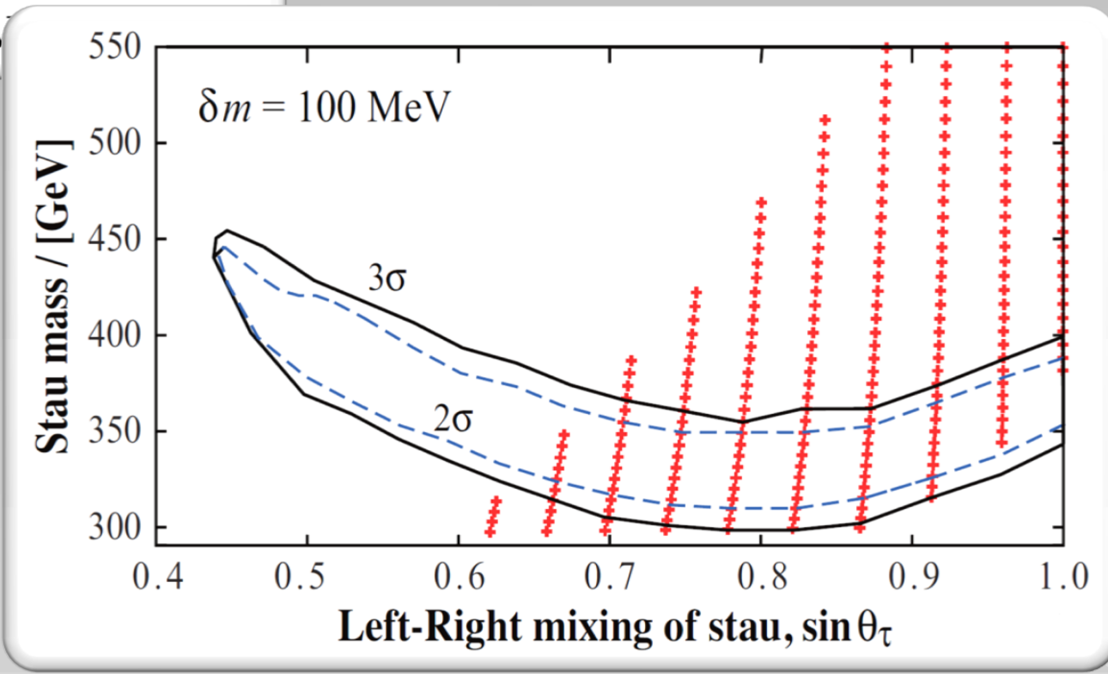
Pale blue region:
Excluded by d over-production

Pale pink region:
Excluded by t over-production

Blue region:
Excluded by ^{6}Li over-production



DM abundance
WMAP
10 MeV
10 MeV(thermal)
50 MeV
50 MeV(thermal)
100 MeV
100 MeV(thermal)
10^{-12}
10^{-13}
0.1
0.07
0.04
0.01
Relic density of the stau $Y_{\tilde{\tau}}$
Temperature (GeV



δm = 100 MeV
3σ
2σ
550
500
450
400
350
300
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Stau mass / [GeV]
Left-Right mixing of stau, sin θ_τ